AIRBORNE OIL SPILL SENSOR TESTING: PROGRESS AND RECENT DEVELOPMENTS

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ABSTRACT: *It is now possible to measure the thickness of an oil slick on water by remote sensing. A laboratory sensor has been developed to provide this absolute oil slick thickness measurement. A joint project between Environment Canada, U.S. Minerals Management Service (MMS), Imperial Oil Research Ltd., and Industrial Materials Institute of the National Research Council of Canada has led to the development of a prototype slick thickness measurement system, known as the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor. This prototype was the first step in achieving the ultimate goal of providing an airborne sensor for the remote measurement of oil slick thickness on water. The LURSOT sensor employs three lasers to produce and measure the time-of-flight of ultrasonic waves in oil, hence providing a direct measurement of oil slick thickness. The successful application of this technology to the measurement of oil slick thickness will benefit (1) the scientific community as a whole by providing information about the dynamics of oil slick spreading and (2) the spill responder by providing a measurement of the effectiveness of spill countermeasures such as dispersant application.*

The first part of this paper provides initial results from laboratory testing prior to a second round of airborne test flights of the modified LURSOT system. The second part of this paper provides details on a new generation of laser fluorosensor, known as Scanning Laser Environmental Airborne Fluorosensor (SLEAF). SLEAF recently has been installed on Environment Canada's DC-3 aircraft. SLEAF incorporates a high-power excimer laser, high-resolution range-gated intensified diode-array spectrometer, and a pair of variable speed and angular displacement scanning mirrors. These scanning mirrors provide SLEAF with the across-track sampling pattern needed to detect narrow bands of oil that can pile up along the high tide lines of beaches and shorelines.

Ground testing of SLEAF has now been underway for some time. This paper provides details of the sensor installation and testing program, and illustrates the operational capabilities of the new system. It is believed that this new sensor will provide prompt reliable detection and mapping of oil contamination in a variety of marine and terrestrial environments.

Oil slick thickness measurement

Scientists and spill response personnel have long been searching for a precise way to measure oil-on-water slick thickness. Until recently, there was no reliable laboratory or field method to provide an accurate measurement of oil slick thickness. Knowledge of slick thickness will result in more effective direction of oil spill countermeasures, including dispersant application and *in situ* burning. In reality, the effectiveness of specific dispersants could be determined quantitatively by the accurate measurement of the oil remaining on the water surface following dispersant application. Furthermore, the ability to measure oil slick thickness should provide significant advances to the fundamental understanding of the dynamics of oil slick spreading.

The LURSOT system. The Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) system has been developed under contract by the Industrial Materials Institute (IMI) of the National Research Council of Canada in Boucherville, Québec. Complete details of the LURSOT system are beyond the scope of this paper; however, selected details of the development are presented below. The LURSOT sensor is a three-laser system, with one of the lasers coupled to an optical interferometer to measure oil slick thickness accurately. The thickness measurement process commences with the absorption of a powerful CO_2 laser pulse (infrared), which creates a thermal pulse in the oil layer. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed. This leads to a step-like rise of the sample surface and the creation of an acoustic pulse. The acoustic pulse moves down through the oil layer until it reaches the oil-water interface, where it is partially transmitted (~85%) and partially reflected back (~15%) towards the oil-air interface, causing a minute displacement of the oil surface. The amount of time required for acoustic pulse to travel through the oil and back to the surfae again is a function of the thickness of the oil layer and the acoustic velocity of the oil. The displacement of the oil layer is measured by a probe laser beam (Nd:YAG) aimed at the surface. Motion of the surface causes a phase or frequency (Doppler) shift in the reflected probe beam. The modulation of the probe beam subsequently is demodulated with an optical interferometer (in this case a photo-refractive crystal). The absolute oil slick thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil layer.

The LURSOT system uses a third laser (a continuous wave HeNe laser) to examine the water surface and generate a trigger pulse when the correct surface geometry for measurement exists. The minimum detectable oil thickness layer that can be measured with the present LURSOT configuration is 700 µm, and the maximum is 38 mm. Signal-processing techniques such as adaptive filtering could be used to measure oil thicknesses below 700 µm.

The initial attempt to test the LURSOT system in an airborne environment was unsuccessful for several reasons (Brown *et al.*, 1994). Briefly, the extreme operating environment provided by a moving platform was radically different from the laboratory setting in which the prototype LURSOT was developed. The intense vibrations experienced in the airborne environment lead to the elimination of the confocal Fabry-Pérot interferometer in favor of a photo-refractive crystal detector for probe laser phase demodulation. The Photo-Refractive Optical Ultrasonic Detector (PROUD) was developed by IMI to provide a demodulation device that is insensitive to vibrations. The PROUD detector is, however, sensitive to frequency changes caused by motion of the target relative to the laser source (in the aircraft).

To compensate for these frequency (Doppler) shifts, an optical frequency compensation device (OFCD) was devised and tested. To employ the OFCD onboard an aircraft, a measurement of vertical velocity must be provided. This was accomplished through the development of a vertical velocity sensor (VVS) by the Institute for Aerospace Research at the National Research Council of Canada in Ottawa. The VVS couples a Differential Global Positioning System (DGPS) receiver with an accelerometer to provide accurate real-time vertical velocity measurement. The VVS was tested onboard the DC-3 and found to operate satisfactorily when isolated mechanically from the floor of the aircraft and filtered appropriately (Brown *et al.*, 1997).

A decision was made to construct a device to measure the instantaneous optical frequency of the returning target laser beam. This device provides a diagnostic as to how well the OFCD is functioning. In addition, this device will provide data on the severity of the Doppler shift induced on the probe laser during normal test conditions of the LURSOT. The broad range of temperatures encountered in the aircraft created differences within the optical beam path of the probe laser (Nd:YAG) that were outside acceptable limits. To rectify this, a novel compact laser system was developed and mounted on a zero thermal expansion carbon-epoxy optical breadboard.

In addition to the known problems associated with operation in the airborne environment, there were concerns about the possible loss of co-linearity of the laser beams employed in the LURSOT system. To understand the effect of vibrations on the co-linearity of the optical system, the University of Toronto's Aerospace Institute undertook a complete theoretical analysis of the support structure that houses the optical and laser components. The investigation revealed several shortcomings with the initial structure and provided the information required to design a structure that provides the stability required to ensure co-linearity of the laser beams at the operating altitude of 300 feet. The new structure was constructed under contract by Aérotech Incorporated, Laval, Québec.

To better visualize the level of misalignment, if any, in actual flight conditions, a system has been developed to measure the in-flight co-linearity of the generation and detection beams employed in the LURSOT system. The system employs a mirror to image the two laser beams onto a thin plate of blackened aluminum. The laser beams, in turn, heat a spot on the aluminum plate, and a thermal infrared (IR) camera captures an image of these "hot" spots. A suitable delay is added so that each beam can be observed sequentially. The image sequences of the IR camera are digitized and stored for processing in a computer. During flight, a mirror can be moved into position to divert the laser beams onto the aluminum plate (if desired for verification of co-linearity). The positions of the two beams subsequently are determined through analysis of the IR camera images, and beam co-linearity/overlap is confirmed.

The redesigned LURSOT system was assembled at IMI and extensively tested in a large-scale laboratory environment to confirm functionality of individual components and the successful measurement of actual oil slick thickness. Individual components of the LURSOT system in the new support structure are shown in Figures 1 and 2.

LURSOT flight test program. The re-engineered LURSOT has now been transported to the Emergencies Science Division's (ESD) hangar facilities in Ottawa where it is being installed on ESD's DC-3 and undergoing a final certification process. Following installation, the LURSOT will undergo a series of four flight tests. These flights will allow for the systematic testing of individual components of the LURSOT system, culminating with the airborne measurement of oil slick thickness.

Figure 1. New LURSOT support structure illustrating telescope (lower left), CO_2 laser (centre), beam co-linearity monitoring device (upper left), and focusing optics (right).

Figure 2. New LURSOT support structure illustrating Doppler shift compensation device (upper left), detection laser (center), and MISER controller (upper right).

Flight 1: In-flight verification of individual components. The initial tests will verify that each component of the LURSOT system operates properly under normal flight conditions. During these tests, no laser beams will exit the aircraft. The following items will be addressed:

- Verify that the in-flight laser output power (each of the three lasers) is equal or close to the nominal values measured on the ground.
- Verify the in-flight performance of the photo-refractive device for the measurement of a phase modulation of the detection laser (equivalent to a laser-ultrasonic modulation). For these tests, an optical phase modulator will be used to induce a known phase variation of the detection laser output. The output of the detection laser will then be injected directly in the collection telescope of the LURSOT, bypassing the focusing optics.
- Verify the in-flight co-linearity of the three laser beams at the output of lasers—the generation and detection lasers are within the overlap criteria (distance between the beam spots less or equal to the beam spot sizes at 300 feet) for normal flight conditions.

Flight 2: Verification of triggering mechanism. This test will verify the triggering mechanism of the LURSOT system. For this test, only the triggering laser (HeNe) will exit the aircraft. This test will be made over a lake or river.

Flight 3: Verification of vertical velocity compensation device. The third test flight will verify the proper operation of the vertical velocity compensation device (VVDC). During these test, both the triggering and detection laser beams will exit the aircraft.

Flight 4: Airborne test of the complete LURSOT system. Following verification of acceptable airborne operation of individual LURSOT system components, a final set of test flights will focus on acquiring an airborne measurement of oil slick thickness. First, a signal will be collected over a body of water, such as a lake, without an oil layer. The laser-ultrasonic signal would consist of the “surface signal” generated by the initial thermal expansion of the water surface, caused by the absorption of the generation laser. Following the successful collection of a laser-ultrasonic signal over a large body of water, flights over man-made pools of oil on water will be conducted. Laser-ultrasonic signals will be recorded, and the thickness of the oil layers will be determined.

Laser fluorosensor development

Airborne laser fluorosensors are unique sensors in that they can unambiguously detect oil in marine and coastal environments including those containing snow and ice. In recent years, a number of laser fluorosensor systems have been developed (Anderson, 1994; Barbini *et al.*, 1991; Brown *et al.*, 1996a, b; Calleri and Bernardi, 1993; Castagnoli *et al.*, 1986; Gruner *et al.*, 1991; Koechler *et al.*, 1992). Most of these fluorosensors have been shipborne instruments that were mounted in aircraft for the occasional airborne mission. Of the few dedicated airborne systems, only two have the crosstrack scanning capabilities necessary to examine beaches and shorelines (Brown *et al.*, 1996a, b; Gruner *et al.*, 1991). The Scanning Laser Environmental Airborne Fluorosensor (SLEAF) system recently developed by ESD provides this functionality and also offers a choice of narrow- or wide-swath widths. SLEAF was designed with the intention of providing real-time detection, classification, and mapping of oil contamination in the marine environment. The system has been constructed, tested, and recently was integrated into Environment Canada’s DC-3 aircraft in preparation for final ground tests and airborne testing.

The SLEAF system. Complete details of the SLEAF system have been provided in earlier publications (Brown *et al.*, 1996a, b). Fluorescence excitation in the SLEAF system is provided by a 100 mJ/pulse, 308 nm XeCl excimer laser (Lambda Physik, LPX140i) operating at rates of up to 400 Hz. Detection of the laser-induced fluorescence is accomplished with a spectrometric receiver consisting of a 22-cm diameter, f/3.3 Newtonian parabolic mirror, with a 1×3 mrad field-of-view, a concave holographic grating, and an intensified diode-array detector (Princeton Instruments, 64 spectral channels, 330 to 610 nm). The detector is range-gated to collect only the laser-induced fluorescence, while rejecting most of the background solar radiation. A pair of scanner heads (Optech Inc., see Figure 3) is employed to provide a choice of narrow- or wide-swath coverage (one-sixth or one-third of the normal operating altitude of 300–600 meters).

Full-spectral resolution, geo-referenced, fluorescence data are collected for each laser pulse and recorded on digital data tapes (8-mm Exabyte). Individual fluorescence spectra are analyzed in real-time to determine the presence or lack of oil in the sensor

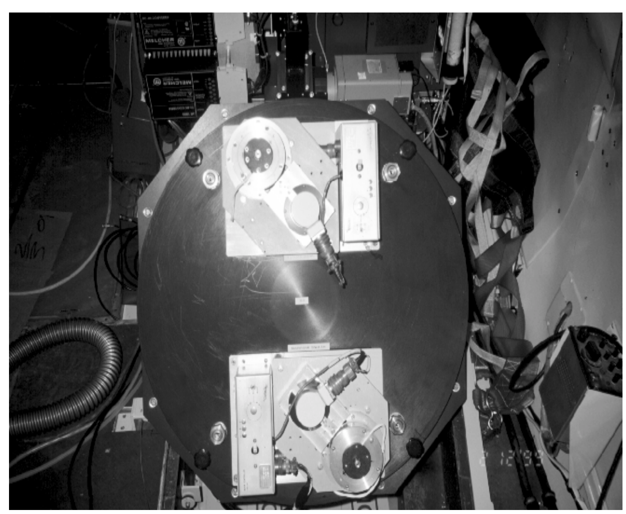

Figure 3. SLEAF narrow- and wide-swath scanner heads.

field-of-view. Principle component analysis (James and Dick, 1996) is used to classify the oil type as light refined, crude, or heavy refined and the extent of oil coverage in each pixel as clean, light, moderate, or heavy. Concise oil contamination information is displayed on the operator's monitor and on faxable hardcopy maps. Oil type is identified on the operator's monitor by color and by way of a text message on the hardcopy map. Oil coverage is represented by the length of a line perpendicular to the flight path of the aircraft.

Since the amount of oil classification and coverage information is substantial, results are averaged over an area approximately 50 meters long by one-half the swath width on either side of the aircraft. This averaging allows for a more concise and readable summary of oil contamination. Both the raw spectral data and the processed oil contamination information are stored on data tape. Time-history displays provide the SLEAF operator with recent system status information. Hardcopy maps with geo-referenced oil contamination information are produced in an 8.5 × 11 inch format onboard the aircraft. The operator has the choice to print all the mission flight area or only areas that contain oil contamination.

DC-3 modifications. Following the successful completion of a factory acceptance test, the individual SLEAF components were delivered to Environment Canada. Upon arrival at the ESD hangars in Ottawa, the system was assembled for further testing and installation in ESD's DC-3 aircraft.

ESD's DC-3 aircraft (C-GRSB) was modified to allow for integration of the SLEAF system. Deca Aviation was contracted to conduct an engineering study to determine the loading capacity of the sensor bay area of the aircraft. A large mounting structure that allows for the rapid installation and/or removal of the SLEAF from the aircraft was then designed and fabricated. To quickly move the SLEAF into position over the sensor bays, a large hydraulic crane was constructed. A cradle was then fabricated to allow for pick up of the SLEAF with the crane and subsequent movement into the aircraft. The SLEAF excimer laser uses 208 volt three-phase power supplied by six synchronized 400 Hz power invertors. In addition, two 60 Hz, 115 volt power invertors were placed in the forward racks of the aircraft. A third 19-inch dual equipment rack was added to the DC-3 to accommodate additional oil spill sensor electronics to complement the SLEAF system.

The SLEAF system has now been integrated into ESD's DC-3 (see Figure 4). Following final alignment of the laser and telescope on the ground, SLEAF was test flown in the Ottawa area on May 25, 2000. Over the next few months, a series of test flights will be undertaken to test the reliability of the hardware during flight, and the ability to withstand repeated take-offs and landing cycles. Operation of the SLEAF will be tested over hard terrain and marine environments. Following flights over uncontaminated targets, the SLEAF will be tested over known sources of oil contamination.

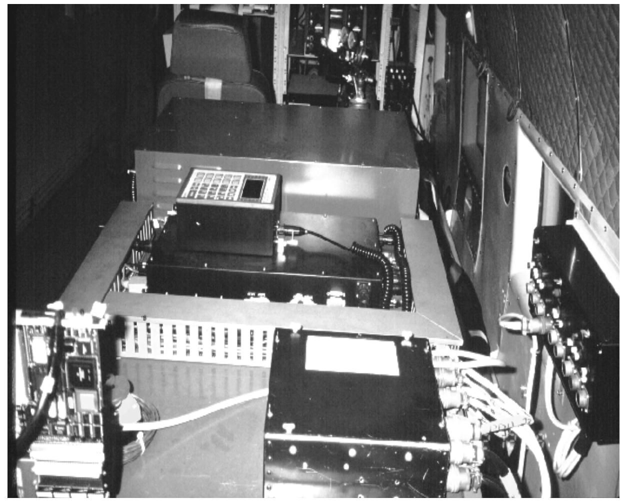

Figure 4. The SLEAF system inside Environment Canada's DC-3.

Conclusions

The redesigned LURSOT system has demonstrated the absolute measurement of oil-on-water slick thickness in the laboratory environment. As such, LURSOT provides the scientific community with a device with which to study the fundamentals of oil slick spreading. The ultimate goal of this project—airborne measurement of oil slick thickness—is now imminent. Successful completion of the airborne testing phase of this project will provide the spill response community with an airborne sensor that can provide information required to make effective, well-informed oil spill countermeasure decisions.

Following an extensive period of design and development, SLEAF has been integrated into Environment Canada's DC-3 remote-sensing aircraft. The initial test flight of the system has been conducted. Upon completion of the entire test flight program, the SLEAF system will be declared operational. SLEAF will then be ready to provide reliable oil contamination information to the spill response community from remote-sensing flights over marine and terrestrial environments.

Biography

Carl Brown is a scientist working in oil spill remote-sensing research and development. His specialties include airborne oil spill sensor development and the application of laser technologies to environmental problems. He has a doctorate degree in physical chemistry and a Bachelor of Technology degree. He has authored over 80 papers and publications.

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